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CAPACITIVE DISCHARGE METHOD FOR COAL DUST EXPLOSIBILITY TESTS

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Canadian Explosives Research Laboratory

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by

K.C. Cheng*, E. Contestabile* and K.K. Feng**

ABSTRACT

We are establishing a high voltage capacitive discharge system to produce electrical sparks of known magnitude and time duration as an ignition source in the Hartmann chamber for methane/coal dust explosion tests. The ignition energy delivered at the spark gap can be calculated by integrating the current discharge profile and multiplying it by the voltage drop measured across the air gap. Thus the minimum energy for initiating a gas or dust explosion can be determined. This method is more accurate in determining the minimum ignition energy as compared to the original Hartmann technique where the source energy = $1/2\ CV_o^2$ was considered to be the ignition energy. This report describes a preliminary evaluation of the effects of spark characteristics and the changes of ignition energies when the source voltage, the capacitance, the damping resistance and the air gap distance are varied. Three basic discharging modes, i.e., oscillatory, short single pulse and unidirectional discharge were used for the preliminary tests for the initiation of coal dust explosions and the results indicated that the probability of dust explosions at a given dust concentration is a function of the magnitude of ignition energy and the duration of discharge time.

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METHODE DE DECHARGE A CAPACITE ELECTRIQUE EMPLOYEE LORS D'ESSAIS SUR LE CARACTERE EXPLOSIF DE POUSSIERES DE CHARBON

par

K.C. Cheng*, E. Contestabile* et K.K. Feng**

RÉSUMÉ

Nous sommes à mettre au point un système de décharge à capacité de tension très élevée dans le but de produire, dans la chambre Hartmann, comme source d'amorçage, une étincelle électrique d'une intensité et d'une durée connues lors d'essais sur les poussières de charbon dans un atmosphère de méthane. En intégrant le profil de la décharge électrique et par multiplication de celle-ci par le gain de tension mesuré entre le vide, il est possible de calculer l'énergie d'allumage reçue à l'éclateur. De cette façon l'on peut déterminer l'énergie minimum requise pour provoquer l'amorçage d'une explosion de gaz ou de poussières de charbon. Cette méthode pour la détermination, de l'énergie d'allumage minimale requise est plus précise comparativement à celle de la technique originale Hartmann où l'on considérait comme énergie d'allumage, cette source énergétique équivalente à $1/2\ CV_o^2$. Ce rapport consiste en une évaluation préliminaire des effets d'allumage et des changements d'énergie d'allumage suite à des variations apportées quant à la source de tension, la capacitance, la résistance de façonnement d'impulsions et l'espacement du vide. Les essais préliminaires pour l'amorçage d'explosions de poussières de charbon ont porté sur trois types élémentaires de décharge électrique, i.e., oscillatoire, courte impulsion simple et décharge unidirectionnelle. Les résultats de ces tests ont démontré que la probabilité de déclenchement d'explosions de poussières pour une concentration donnée est fonction de l'intensité de l'énergie d'allumage et de la durée du temps de décharge.

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INTRODUCTION

Methane-coal dust explosions have always been a major hazard in underground coal mine operations. As mining progresses, the coal dust deposits at and near the working-face area, the conveyor roadways and the return airways. When a gas explosion occurs, the shock waves tend to disperse these dusts and the explosion is propagated by flames as long as the dust cloud or methane-coal dust mixture in the air is maintained within the lower and upper explosive limits.

The Hartmann apparatus and related test procedures have been developed by the U.S. Bureau of Mines and used for over fifty years as a standard method to determine the explosibility of flammable dust materials (1). The detailed information on explosibilities of American coal dusts was reported in reference (2) where the explosibility index of Pittsburgh coal is defined as 1 and other explosive dusts are compared with this standard index. The parameters that determine this index are the ignition temperature, the minimum ignition energy, the minimum explosive dust concentration, the maximum pressure generated and the maximum rate of pressure rise. The minimum ignition energy for Pittsburgh coal dust was determined to be 60 mJ in source energy with the use of a capacitive discharge technique. For the same coal, the minimum explosive concentration was determined to be 55 g/m^3 with the use of AC sparking technique. Both of the above values were obtained in the original 1.23 L Hartmann chamber (2).

The Hartmann technique has been adopted world-wide, however, there appear to be large variations in the results obtained by different laboratories on the same materials. For example, the minimum explosive concentration for Pittsburgh coal dusts has been reported in different papers to be in the range of 30 to 300 g/m^3 (3). The minimum explosive concentration for Pittsburgh coal dust tested on the Hartmann apparatus in our laboratory was between 60 and 80 g/m^3. The level of minimum dust concentration was obtained by the Bruceton up-and-down method and represents a 50% chance of explosibility. Recently it has also been shown that the amount of energy required to initiate an explosion for the lycopodium powder that has a uniform particle size, varies with the dust concentrations (4). It indicated that the minimum explosive dust concentration varies with the magnitude of the ignition energy input.

The Hartmann apparatus have been used at our laboratory for testing the explosibility of Canadian coals. With the use of AC sparking, only the minimum dust concentration, the explosion pressure and the rate of pressure rise were determined for some of the coal samples. Currently we are establishing a high voltage capacitive discharge system to produce sparks of known magnitude and duration as the ignition source in the Hartmann chamber. Thus the ignition energy delivered at the spark gap can be calculated by integrating the current profile and multiplying it by the voltage drop measured across the spark gap. This method is more accurate in determining the minimum ignition energy as compared to the original Hartmann technique where the source energy = $1/2\ CV_o^2$ was considered to be the ignition energy. This report describes the preliminary evaluation of the effects of the spark characteristics and the changes in ignition energies when the source voltage, the source capacitance, the damping resistance and the spark gap distance are varied.

CHARACTERISTICS OF CAPACITIVE DISCHARGE CIRCUIT

By adding a damping resistance in series with the spark gap in a capacitive discharge circuit, the profile of discharging current through the spark gap can be modified from an oscillatory form (underdamped) to an unidirectional one (critically damped or over damped). The efficiency in the delivery of energy at the spark gap can be varied from about 1% to 20% of the charged energy (5,6). The advantage of this modification is that it enables one to calculate the electrical energy dissipated at the spark gap. Figure 1 shows a schematic of the capacitive discharge system that has been used at our laboratory to provide the DC ignition sparks for the Hartmann apparatus. The pulse generator with high voltage power supply made by Universal Voltronics Corp. consists of various capacitors ranging in value from 100 pF to 25,600 pF and a voltage regulator for the voltage setting of up to 50 kV. It was found that the system was not energetic enough for testing coal dust explosion due to a low percentage of energy delivered at the spark gap. Later, three additional capacitors (0.05, 0.10 and 0.22 μF) and some high voltage resistors (100 to 100 k ohms) were purchased to meet the needs for a greater capacity and longer discharge time.

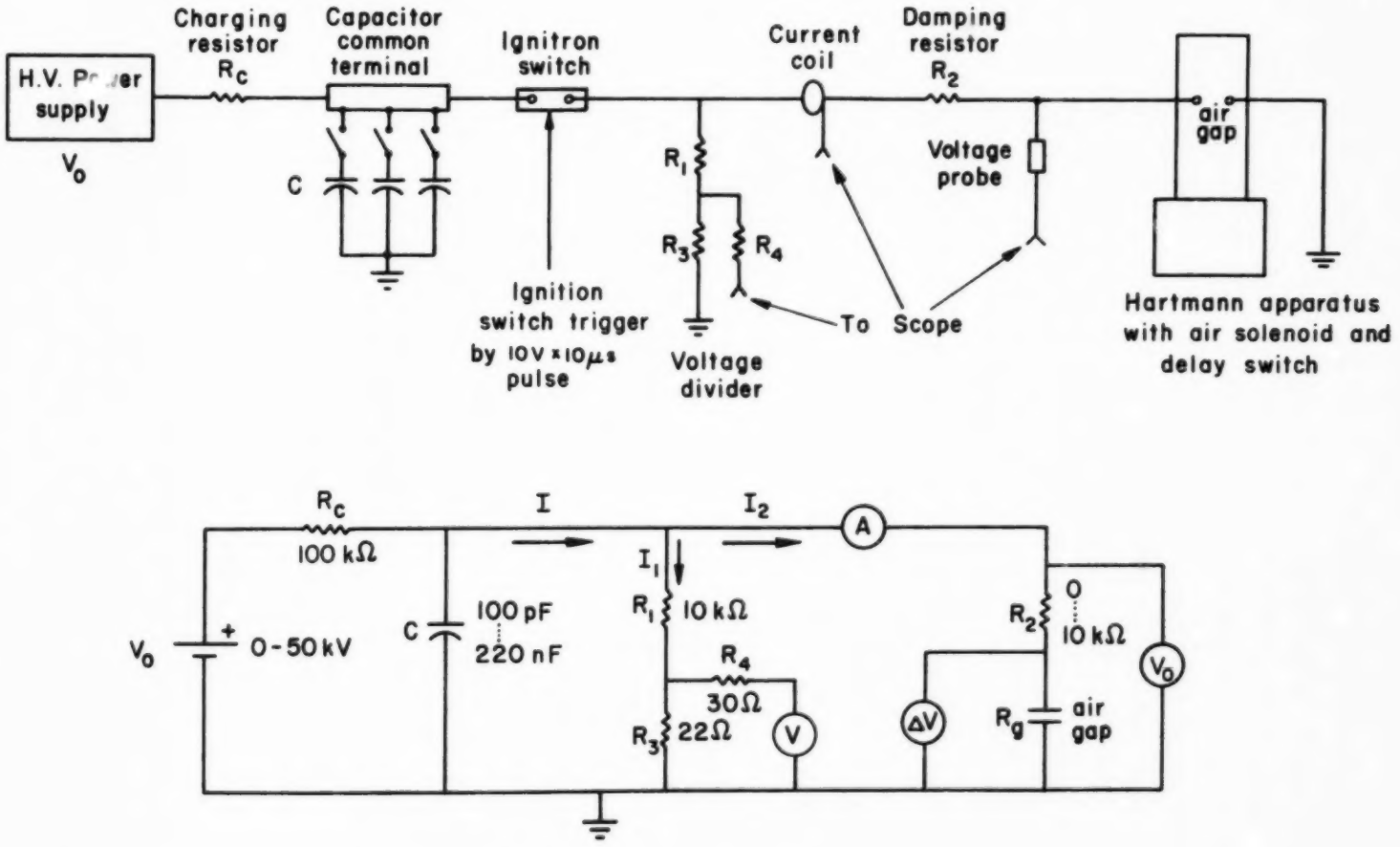
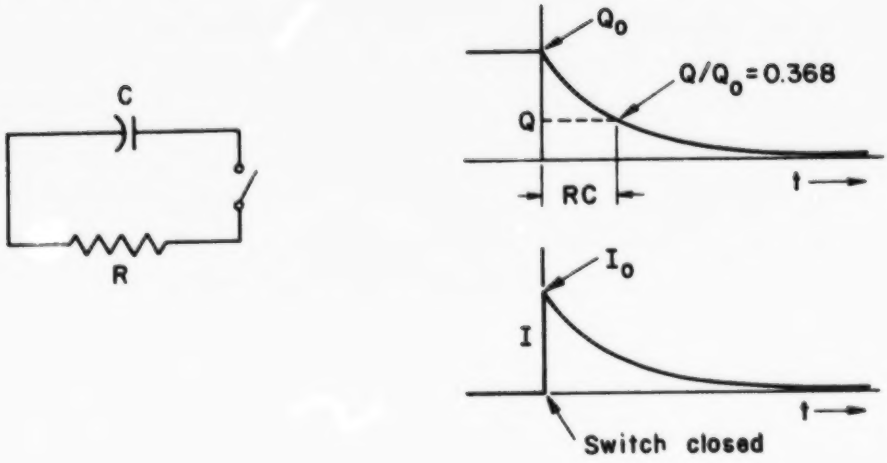
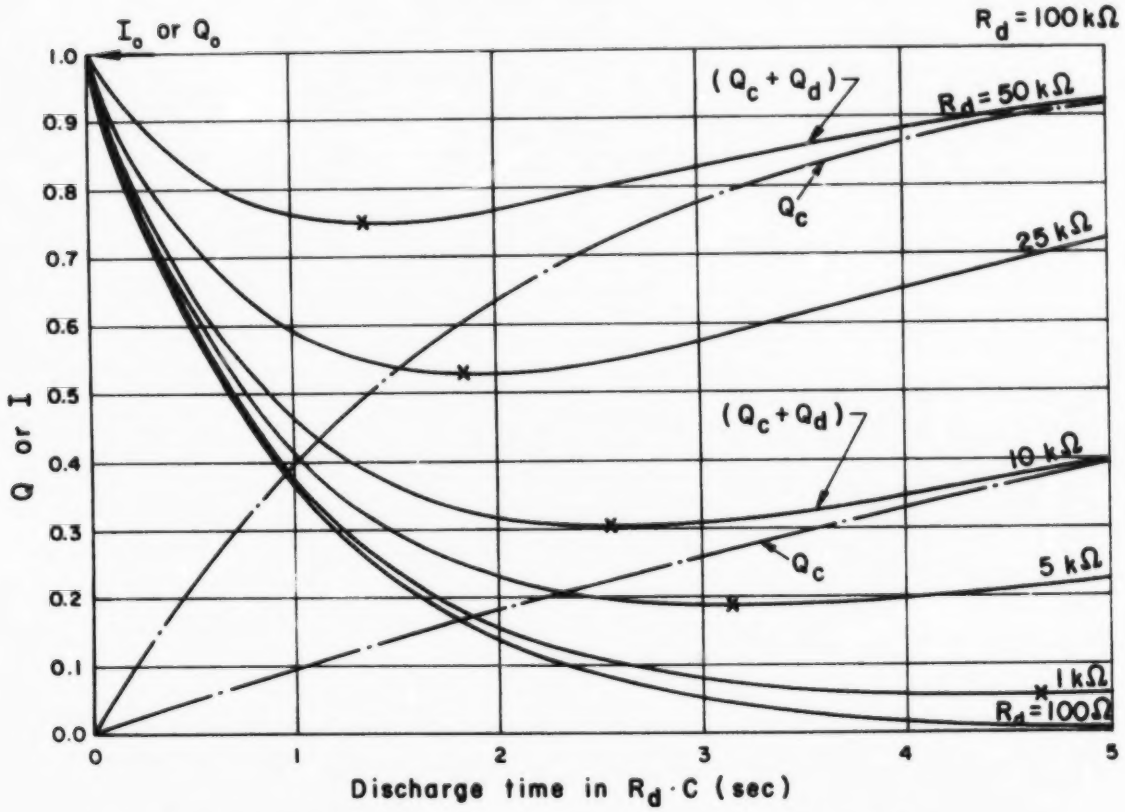


Fig. 1 - Schematic of capacitive discharge circuit for spark ignition



(a) Single RC discharging circuit



(b) Composite RC discharging circuit with $R_c = 100\,k\Omega$

Fig. 2 - Electrostatic charge and current decays in an RC circuit

Figure 2(a) shows a single loop RC circuit where the capacitor has been charged to a potential of V_o and then discharged through the resistance R by closing the switch. Figure 2(b) shows a composite RC circuit that is discharging and charging simultaneously. The capacitive discharge instrumentation used in our work is similar to the composite RC circuit. The mathematical relationships between the electrostatic charge (Q in coulomb), the capacitance (C in farad), the stored energy (U in joule), the resistance (R in ohm), the voltage (V in volt), the discharge current (I in ampere) and the discharge time (t in second), are as follows (7,8,9):

(a) For a single loop RC circuit;

$$Q = C \cdot V \tag{1}$$

$$Q = Q_o \cdot \mathrm{Exp}(-t/RC) = C \cdot V_o \cdot \mathrm{Exp}(-t/RC) \tag{2}$$

$$I = I_o \cdot \mathrm{Exp}(-t/RC) = \frac{Q_o}{RC} \cdot \mathrm{Exp}(-t/RC) = \frac{V_o}{R} \cdot \mathrm{Exp}(-t/RC) \tag{3}$$

$$V = V_o \cdot \mathrm{Exp}(-t/RC) = I_o \cdot R \cdot \mathrm{Exp}(-t/RC) \tag{4}$$

$$U = \frac{1}{2} \cdot Q_o \cdot V_o = \frac{1}{2} \cdot C \cdot V_o^2 \tag{5}$$

(b) For a composite RC circuit;

$$Q = Q_d + Q_c = [\mathrm{Exp}(-t/R_d \cdot C) + 1 - \mathrm{Exp}(-t/R_c \cdot C)]Q_o \tag{6}$$

$$I = [\mathrm{Exp}(-t/R_d \cdot C) + 1 - \mathrm{Exp}(-t/R_c \cdot C)]I_o \tag{7}$$

where Q_d is the charge remaining in the capacitor during a single discharging period and Q_c is the charge increased concurrently from the charging circuit. The following equation can be used to calculate a critical time, T_{crit} when the charge in the capacitor reduces to a minimum value. After this critical time, the current discharging processes will not obey the exponential decay law.

$$T_{crit} = \frac{R_c \cdot R_d \cdot C}{(R_c - R_d)} \cdot \ln \frac{R_c}{R_d} \qquad (8)$$

The resistance and voltage drop across the air gap of electrodes are relatively small as compared to the value of the damping resistance, and the voltage drop across it. The resistance between the air gap varies considerably depending on factors such as the charge density, the degree of air ionization, the discharge time constant and the turbulent condition of the airstream at the electrodes. It is difficult to establish a simple mathematical relationship for the determination of voltage changes at the spark gap. Therefore a voltage probe is used to monitor this voltage.

For a set of parallel-plate electrodes separated by air, the minimal breakdown voltage across the air gap can be estimated (8) by:

$$V = 3 \times 10^3 \times D_{air} \qquad (9)$$

where D_{air} is the air gap in mm and V is the breakdown voltage in volts.

With a spark gap setting at 5 mm (3/16 of an inch), this minimal voltage would be 15 kV. However, for pointed electrodes, whose electric field intensity can be much higher than that of parallel-plate electrodes, the breakdown voltage is lower. With the pointed electrodes of the Hartmann apparatus set at 5 mm apart, the breakdown voltage is about 10 kV. As expected, once a breakdown occurs and the current flow is established, the voltage across the electrodes will drop drastically to maintain a continuous discharge. Equation (3) describes the current decay as a function of time. Initially when the switch is closed, the electrostatic charge builds up at the electrodes and establishes the intense electric field responsible for the ionization and the breakdown of the air gap. Thus the current rises to an initial value of $I_o = V_o/R$ at $t = 0$ and then decays exponentially to zero. The time that characterizes the current decay profile is the time constant RC in seconds. One may consider that the current discharging process is completed after a period of 4.6 RC as the charge Q/Q_o remaining in the capacitor is only 1% of the initial quantity. For $t = RC$, the charge remaining in the capacitor is 1/e or 36.8% of the initial quantity.

STUDIES OF MODES OF CURRENT DISCHARGE WITH A COMPOSITE RC CIRCUIT

The profiles of the current discharge and the voltage across the spark gap were studied by varying the capacitance, the damping resistance and the source voltage. Some typical results are shown in Fig. 3. Following are the results obtained on our equipment.

1. Oscillatory discharge: With R = 0, the circuit is underdamped. Both the current and the voltage discharge forms are sinusoidal. The period of ringing pulse is about 7 μs. The percentage of energy deposited at the spark gap is very high but it is difficult to calculate the magnitude of this energy deposition.
2. Short single pulse discharge: With R = 25 - 100 ohms, the circuit is critically damped. The current discharges exponentially and the voltage at the spark gap varies appreciably during discharge. The pulse width varies from about 10 to 50 μs as the damping resistance increases from 25 to 100 ohms. The percentage of energy deposited at the spark gap is difficult to estimate.
3. Unidirectional discharge (or long single pulse discharge): With R = 1 k - 10 k ohms, the circuit is over-damped. The current decays exponentially and is characterized by a long RC time constant. The voltage across the spark gap is fairly constant during discharge and has a plateau of 50-250 volts. The energy deposited at a 5 mm spark gap is generally less than 1.5% of the charged energy.

ENERGY DEPOSITION AT SPARK GAP BY UNIDIRECTIONAL CAPACITIVE DISCHARGE

With a long RC time constant greater than 100 μs in an over-damped RC circuit as shown in Fig. 3(e), the voltages across the spark gap are fairly constant throughout the discharging period. Thus the electrical energy deposited at the spark gap can be calculated by integrating the current decay curve and multiplying it by the voltage readings across the spark gap. Equation (3) is used to derive Eq (10a) and (10b), which can be used to calculate the spark energy of a unidirectional discharge. Therefore the magnitude and the duration of energies delivered to the Hartmann chamber can be determined.

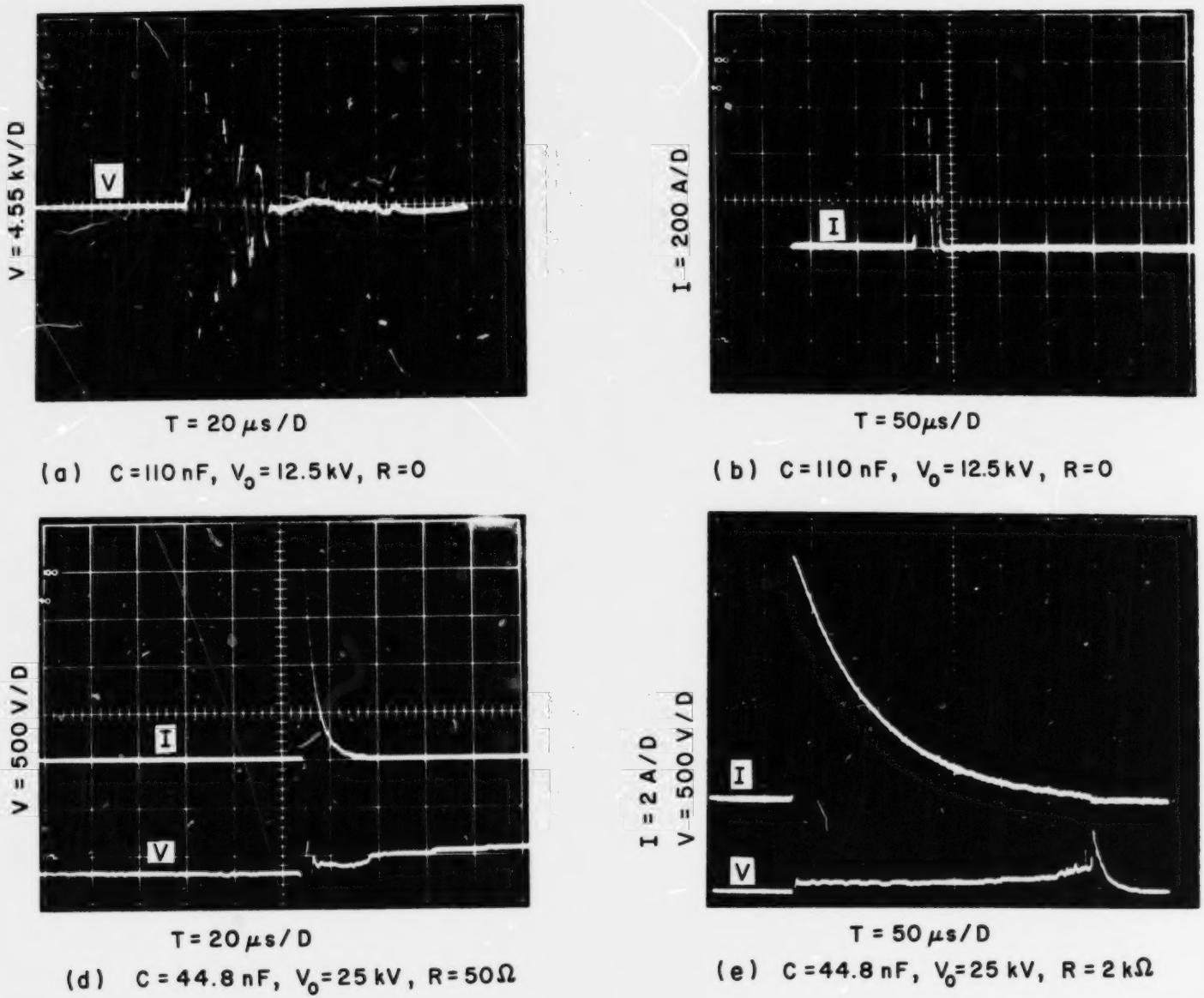

V = 4.55 kV/D
V
T = 20 μs/D
(a) C = 110 nF, V_0 = 12.5 kV, R = 0
I = 200 A/D
I
T = 50 μs/D
(b) C = 110 nF, V_0 = 12.5 kV, R = 0
I = 50 A/D
V = 500 V/D
I
V
T = 20 μs/D
(d) C = 44.8 nF, V_0 = 25 kV, R = 50 Ω
I = 2 A/D
V = 500 V/D
I
V
T = 50 μs/D
(e) C = 44.8 nF, V_0 = 25 kV, R = 2 kΩ

Fig. 3 - Modes of current discharge and voltages across the spark gap in a discharging RC circuit

$$W = \int_0^t I^2 \cdot R_g \, dt = \int_0^t I \, dt \cdot I \cdot R_g = \int_0^t I_o \cdot V_g \cdot \text{Exp}(-t/RC) dt \qquad (10)$$

(a) Without the voltage divider in the circuit;

$$W = I_o \cdot R \cdot C \cdot V_g \, [1-\text{Exp}(-t/RC)] = C \cdot V_o \cdot V_g \, [1-\text{Exp}(-t/RC)]$$

$$= Q_o \cdot V_g [1-\text{Exp}(-t/RC)] \qquad (10a)$$

(b) With the voltage divider in the circuit;

$$W = \frac{R_1}{(R_1+R_2)} \cdot I_o \cdot R \cdot C \cdot V_g [1-\text{Exp}(-t/RC)] = \frac{R_1}{(R_1+R_2)} \cdot C \cdot V_o \cdot V_g [1-\text{Exp}(-t/RC)]$$

$$= I_{o2} \cdot R \cdot C \cdot V_g [1-\text{Exp}(-t/RC)] \qquad (10b)$$

where W = electrical energy dissipated at the air gap of electrodes in J

I_o = peak value of total discharge current in A

I_{o2} = peak value of branching current going through electrodes in A

R = equivalent value of total resistance in ohms including the spark gap resistance (R_g), the resistance of voltage divider (R_1) and the resistance of damping resistor (R_2)

$$R = \frac{R_1 (R_2 + R_g)}{(R_1 + R_2 + R_g)} \simeq \frac{R_1 \cdot R_2}{(R_1 + R_2)}$$

R_g = resistance at spark gap, it is negligible as compared to damping resistance after ionization path is established

C = capacitance in Farads (F)

V_g = voltage across the spark gap in volts

t = time duration of capacitive discharge in seconds.

For example, the energy deposited for the set-up in Fig. 3(e) is:

$$W = 10.5 \times \frac{10 \times 2.5}{(10 + 2.5)} \times 10^3 \times 44.8 \times 10^{-9} \times 100 \, [1 - \text{Exp}(-320/89.6)] = 91.4 \text{ mJ}$$

TEST RESULTS

The current and voltage variations across the electrodes in the Hartmann apparatus were monitored on the oscilloscope by installing a current coil (100 mv/A) and a voltage probe (1:1000 ratio) at the electrodes as illustrated in Fig. 1. The results are shown in Fig. 4, 5, 6 and Tables 1 to 7, inclusive. By alternately varying the source voltage, the capacitance and the damping resistance in the RC circuit, the magnitude and the time duration of a discharge pulse can be varied to give a specific energy level for dust explosion tests. Using the standard Pittsburgh coal dust sample, a series of explosion tests were carried out on the Hartmann apparatus with different energy levels and discharge modes, and found satisfactory results with the preliminary tests. Following is a summary of the experimental results:

(1) When the air gap = 5 mm, V_o = 15 kV, C = 0.1 μF, and the damping resistance is increased, both the pulse duration and the level of plateau voltage (ΔV) increase, but the discharge current and the energy deposition decrease as shown in Fig. 4.

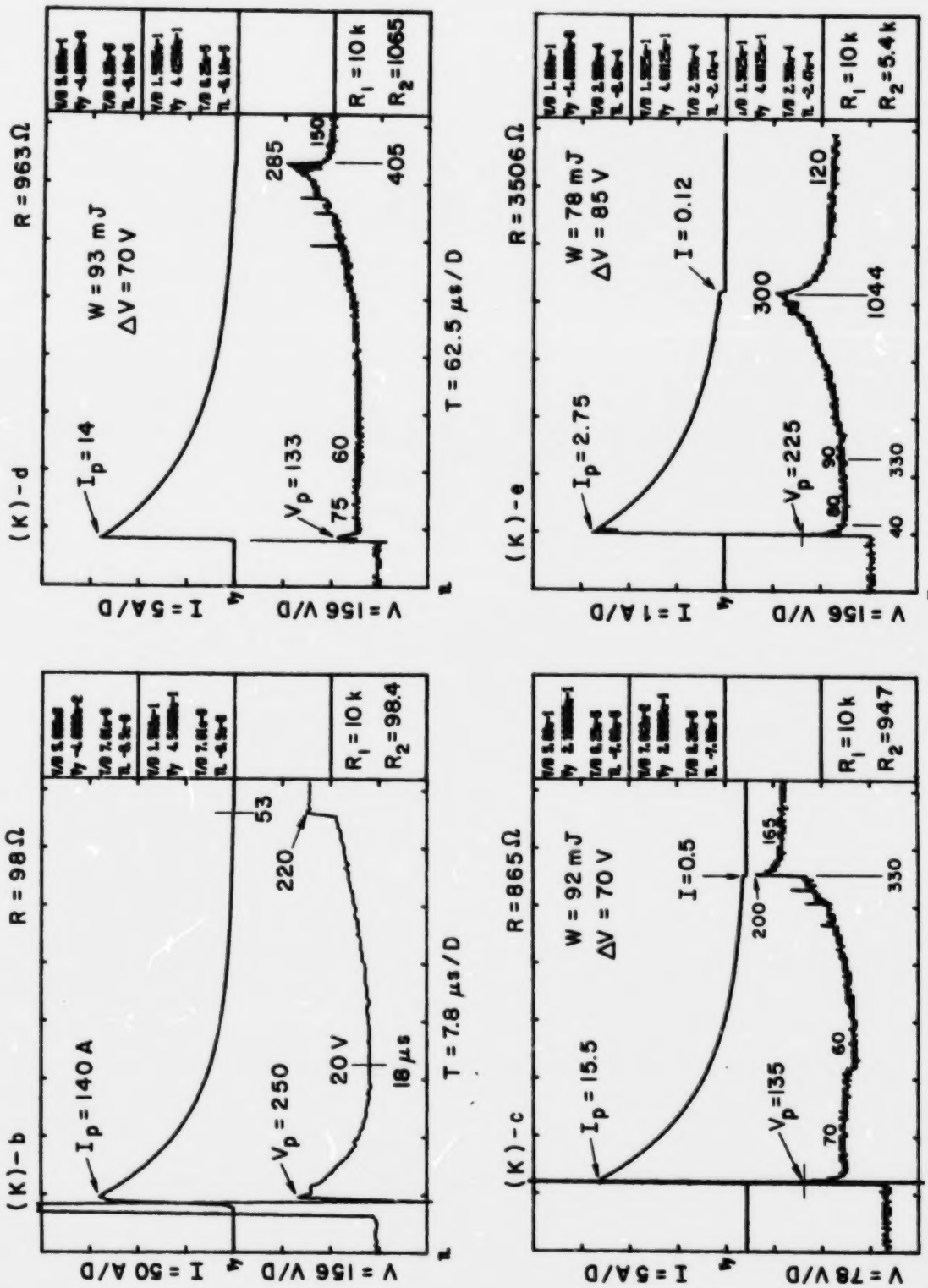
(2) When the air gap = 5 mm, R = 865 ohms, C = 0.1 μF, and the charging voltage is increased, the discharge current and the energy deposition increase as shown in Fig. 5.

(3) When the air gap = 5 mm, V_o = 15 kV, R = 963 ohms, and the capacitance is increased, the discharge time duration and the energy deposition increase almost linearly as shown in Fig. 6.

(4) Tables 1 and 2 show that for unidirectional discharge pulses, the electrical energy deposited at the spark gap are 0.25% to 1.5% of the source energy with the charge voltage setting at between 10 and 30 kV. A higher voltage setting results in a lower percentage of energy deposition.

(5) Tables 3 and 4 show that when the capacitance is increased, the magnitude of energy deposited and the time duration of discharge current increase almost linearly but the percentages of energy deposition at various voltage settings remain practically constant.

(6) Table 5 shows that with C = 25.6 nF and R = 5 kV, when the air gap is increased, the per cent energy delivered at the spark gap is proportional to the gap distance. It also raises the initial breakdown voltage across the air gap.



(Tested at V_o = 15 kV and C = 0.1 μF)

Fig. 4 - Voltage and current at spark gap versus damping resistance

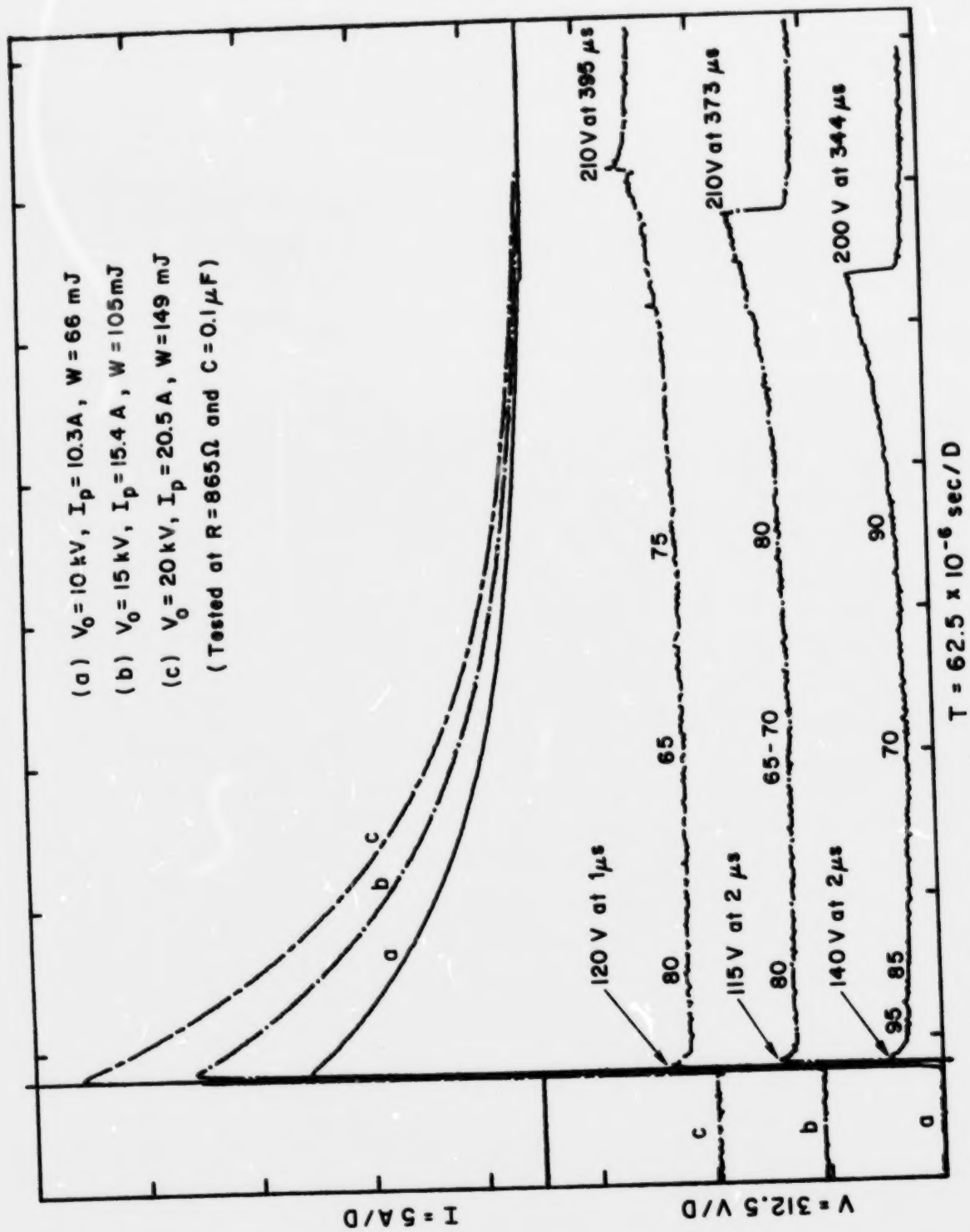


Fig. 5 - Voltage and current at spark gap versus source voltage

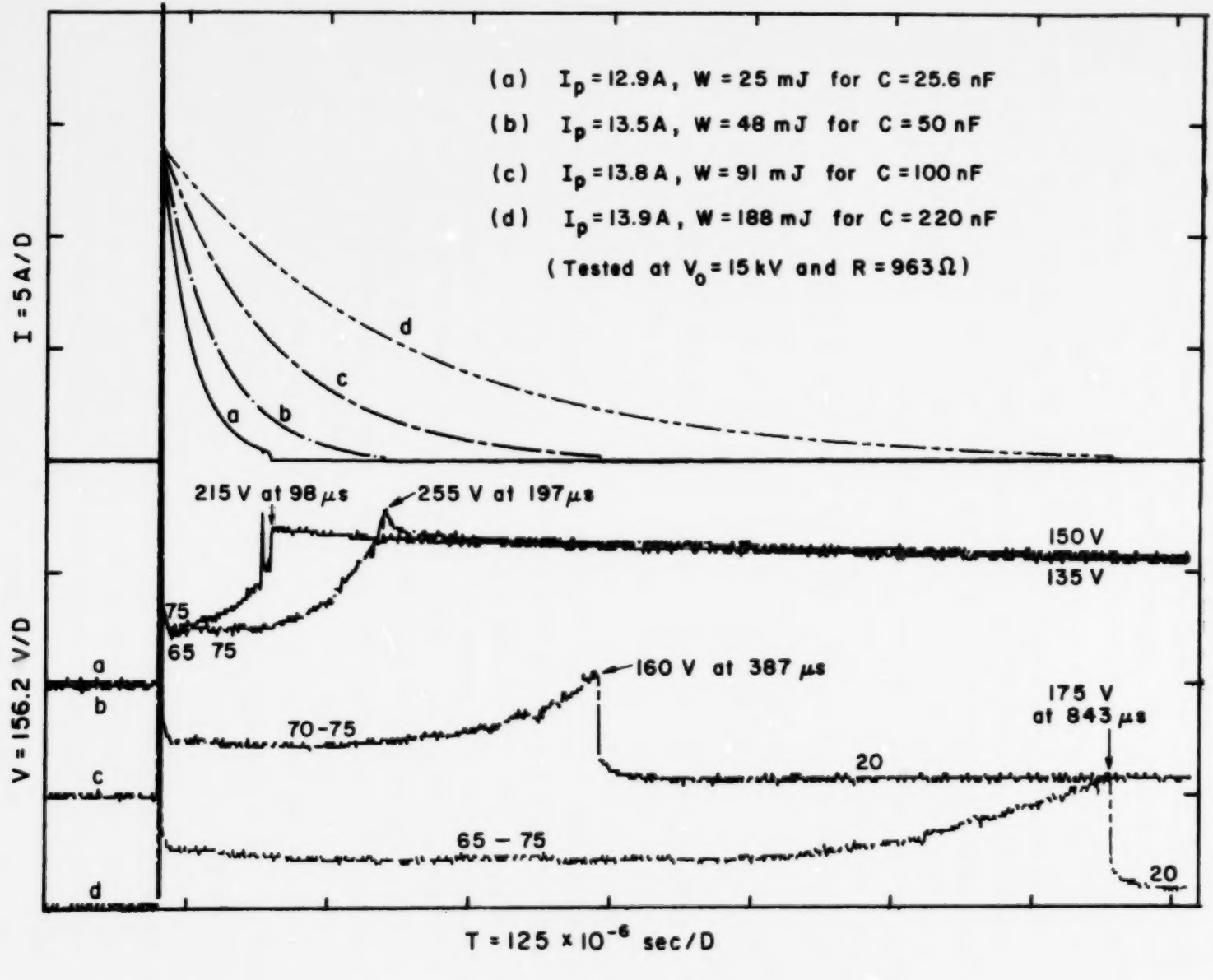

(a) I_p = 12.9A, W = 25 mJ for C = 25.6 nF
(b) I_p = 13.5A, W = 48 mJ for C = 50 nF
(c) I_p = 13.8 A, W = 91 mJ for C = 100 nF
(d) I_p = 13.9 A, W = 188 mJ for C = 220 nF
(Tested at V_0 = 15 kV and R = 963 Ω)
I = 5A/D
d
c
b
a
215 V at 98 μs
255 V at 197 μs
150 V
135 V
75
65 75
a
b
c
d
160 V at 387 μs
175 V
at 843 μs
70-75
20
65 – 75
20
V = 156.2 V/D
T = 125 x 10^{-6} sec/D

Fig. 6 - Voltage and current at spark gap versus capacitance

(7) Table 6 shows that the plateau voltages increase as the damping resistance increases, but decrease as the source voltage increases.

(8) Table 7 shows the preliminary results of coal dust explosibility tests. The per cent explosion represents an average of 10-20 single tests. For a given explosive dust concentration, such as at a concentration of 304 g/m^3 for Pittsburgh coal, the probability of dust explosions decreases as the magnitude of ignition energy is reduced. Using the same magnitude of ignition energy, either by a short single pulse discharge or an oscillatory discharge, it will initiate a dust explosion, but the frequency or percentage of dust explosions is less as compared to that with the unidirectional discharge sparks.

DISCUSSION

1. Plateau voltage: To calculate the energy deposited at the spark gap, we assumed that the plateau voltage is constant throughout the entire discharged period, but it was not quite true. For the unidirectional discharges, there are two regions, preand post-plateau region on the voltage curve, that are required for further studies. Thus the precise amount of energy developed between the electrodes can be determined. In the preplateau region, the voltage generally decreases from a peak value of 150-250 volts to the plateau voltage value. This process occurs during the first 20-40 μs before the ionization path of the electrodes is fully established. In the post-plateau region, the voltage increases gradually from the plateau value to a peak value of 200-300 volts at the end of discharge period. This indicates that the ionization path becomes narrower and the air gap resistance becomes greater towards the end of discharging process.

2. Spark gap distance: The energy deposited at the spark gap is proportional to the air gap distance between the electrodes. When the air gap is increased, the per cent of energy deposited increases because the voltage gain across the gap is increased. But it also raises the breakdown voltage in preventing the establishment of an ionization path. There is a critical condition for a voltage (V_o) setting, at which the discharge current is critically passing through the electrodes and produces an opti-

mal energy output at the spark gap. Currently, we are fabricating a new Hartmann explosion chamber with adjustable electrodes, so that a wide range of spark gaps can be set precisely.

3. Minimum ignition energy: The ignition energy or the so called minimum ignition energy is the minimal amount of energy required for the initiation of explosive materials. The spark energy calculated in this report represents the total amount of energy deposited at the spark gap during a single discharge process. For coal dust explosibility tests, the amount of energy required to initiate a dust explosion is only a fraction of this spark energy. To determine the minimum ignition energy, the exact time when an explosion occurs has to be determined either by detecting the explosion pressure or the ignition flame.

4. Discharge time: The probability of initiating a dust explosion depends on both the energy input and the discharge time. The probability of a dust explosion increases as the magnitude of energy input is increased during a single discharge process. It is anticipated that the probability of dust explosion will vary if the pulse duration is altered with a given constant energy input in a single discharge. The existing equipment was originally designed to provide a maximum RC time constant of 1000 ohms x 50 nF = 50 μs. Currently, we experience a difficulty in obtaining a clear pulse when a damping resistor of 10 k ohms or greater is used. We are planning to improve the system for giving a maximum RC time constant of 100 k ohms x 0.22 μF = 22 ms.

5. Hartmann apparatus and test procedures: There is some degree of inconsistency in the test results produced by different laboratories using the Hartmann technique and the test procedures. Some undefined problems are the sample dispersion by compressed air, the air/arc time delays during triggering, the per cent energy deposited at spark gap vs source voltage, dust/gas explosibility in relation to the magnitude of energy input and time duration, etc.

FUTURE WORK

1. Variations of plateau voltage versus energy depositions at spark gap.

2. Energy deposition vs spark gap distance and critical breakdown voltage.

3. Determination of ignition time and minimum ignition energy.

4. Time duration of pulse discharge vs probability of dust explosion.

5. Evaluation and/or modification of Hartmann apparatus and test procedures.

Table 1 - Energy deposition at spark gap as function of source voltage and damping resistance at C = 110 nF and gap = 0.5 cm

Parameter	R = 0			R = 100 ohms					R = 2.0 k ohms				R = 5 k ohms				
V_o (kV)	10	12.5	15	10	15	20	25	30	10	15	20	25	10	15	20	25	30
I_{o2} (A)	900	1100	1300	90	140	175	230	250	4.1	6.3	8.7	10.9	1	1.5	2.1	2.6	3.2
V_g (V)				(Change from -100 to +80)					100	90	75	60	120	105	90	80	75
RC (ms)						(0.011)					(0.22)				(0.55)		
t (ms)	(0.015 to 0.036)					(0.050)			0.6	0.75	0.82	0.80	1.0	1.15	1.5	1.35	1.62
W (mJ)									84.3	121	140	140	55.3	75.9	97.2	108	125
U (J)									5.5	12.4	22	34.3	5.5	12.4	22	34.3	49.4
W/U (%)									1.53	0.97	0.64	0.41	1.01	0.61	0.44	0.30	0.25
Type of current	oscillatory 5 to 9 pulses			short single pulse					unidirectional discharge				unidirectional discharge				

Table 2 - Energy deposition at spark gap as function of source voltage and damping resistance at C = 44.8 nF and gap = 0.5 cm

Parameter	R = 0			R = 100 ohms					R = 2.0 k ohms				R = 5 k ohms				
V_o (kV)	10	12.5	15	10	15	20	25	30	10	15	20	25	10	15	20	25	30
I_{o2} (A)	560	760	850	90	125	170	200	240	4.2	6.4	8.7	10.8	1.0	1.5	2	2.5	3
V_g (V)				(Change from 200 to 80 to 250)					90	75	70	65	120	100	90	80	75
RC (ms)				(0.0045)					(0.0896)				(0.224)				
t (ms)	(0.008 to 0.025)			(0.020)					0.24	0.26	0.32	0.35	0.50	0.65	0.7	0.7	0.75
W (mJ)									31.5	40.6	53	61.6	24	31.8	38.5	42.8	48.6
U (J)									2.24	5.04	8.96	14	2.24	5.04	8.96	14	20.2
W/U (%)									1.41	0.81	0.59	0.44	1.07	0.63	0.43	0.31	0.24
Type of current	oscillatory 3 to 9 pulses			short single pulse					unidirectional discharge				unidirectional discharge				

Table 3 - Energy deposition at spark gap as function of source voltage and capacitance at R = 2.0 k ohms and gap = 0.5 cm

Parameter	C = 25.6 nF				C = 44.8 nF				C = 65 nF				C = 110 nF			
V_o (kV)	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
I_{o2} (A)	4	6.4	8.5	10.5	4.2	6.4	8.7	10.8	4	6	8	10.5	4.1	6.3	8.7	10.9
V_g (V)	100	90	80	70	90	75	70	65	80	60	50	40	100	90	75	60
RC (ms)	(0.0512)				(0.0896)				(0.130)				(0.220)			
t (ms)	0.15	0.16	0.2	0.22	0.24	0.26	0.32	0.35	0.4	0.4	0.45	0.5	0.6	0.75	0.82	0.8
W (mJ)	19.4	28.2	34.1	37.1	31.5	40.6	53	61.6	39.7	44.6	50.4	53.4	84.3	121	140	140
U (J)	1.28	2.88	5.12	8	2.24	5.04	8.96	14	3.25	7.31	13	20.3	5.5	12.4	22	34.3
W/U (%)	1.51	0.98	0.67	0.46	1.41	0.81	0.59	0.44	1.22	0.61	0.39	0.26	1.53	0.97	0.64	0.41

Table 4 - Energy deposition at spark gap as function of source voltage and capacitance at R = 5.0 k ohms and gap = 0.5 cm

Parameter	C = 25.6 nF				C = 44.8 nF				C = 65 nF				C = 110 nF			
V_o (kV)	10	15	20	25	15	20	25	30	10	15	20	25	10	15	20	25
I_{o2} (A)	1	1.5	2	2.5	1.5	2	2.5	3	1	1.5	2	2.5	1	1.5	2.1	2.6
V_g (V)	125	110	100	90	100	90	80	75	115	100	90	80	120	105	90	80
RC (ms)	(0.128)				(0.224)				(0.325)				(0.55)			
t (ms)	0.25	0.3	0.33	0.35	0.65	0.7	0.7	0.75	0.57	0.7	0.73	0.75	1.0	1.15	1.5	1.35
W (mJ)	13.7	19.1	23.7	26.9	31.8	38.5	42.8	48.6	30.9	43.1	52.3	58.5	55.3	75.9	97.2	105
U (J)	1.28	2.88	5.12	8	5.04	8.96	14	20.2	3.25	7.31	13	20.3	5.5	12.4	22	34.3
W/U (%)	1.07	0.66	0.46	0.34	0.63	0.43	0.31	0.24	0.95	0.59	0.40	0.29	1.01	0.61	0.44	0.30

Table 5 - Energy deposition as function of spark gap distance (at C = 25.6 nF and R = 5 k ohms)

Source voltage	$\frac{CV_o^2}{2}$	Spark gap distance = 0.5 cm (3/16" gap)					Spark gap distance = 0.8 cm (5/16" gap)				
V_o	U	I_{o2}	t	V_g	W	W/U	I_{o2}	t	V_g	W	W/U
(kV)	(J)	(A)	(μs)	(V)	(mJ)	(%)	(A)	(μs)	(V)	(mJ)	(%)
15	2.88	1.5	325	110	19.5	0.68	1.5	250	180	29.7	1.03
20	5.12	2	350	100	24	0.47	2.1	330	165	41	0.80
25	8.00	2.5	350	90	27	0.34	2.7	325	150	47.7	0.60

Table 6 - Plateau voltages (ΔV) versus source voltage and resistance

		V_o = 10 kv			V_o = 15 kv			V_o = 20 kv			V_o = 25 kv		
R (ohms)	C (nF)	I_{o2} (A)	t (μs)	ΔV (V)	I_{o2} (A)	t (μs)	ΔV (V)	I_{o2} (A)	t (μs)	ΔV (V)	I_{o2} (A)	t (μs)	ΔV (V)
100	44.8	95	20	-	145	25	-	190	30	-			
497	50	18.8	207	60	27.9	235	50-55						
497	100	19.2	214	60-65	28.0	250	55-60	37.5	254	50-55			
874	44.8	10.2	145	65-70	14.9	165	65	19.6	180	60-65			
865	100	10.3	344	70	15.4	373	60-70	20.5	395	60-65			
933	44.8	9.6	185	60-65	14.2	190	55-65	19.3	200	55	24.0	215	50
963	44.8	9.1	170	65	13.8	189	60-65	18.0	199	55-60			
963	50				13.9	224	60-65						
963	100	9.2	355	65-75	13.8	387	60-75	18.2	435	60-65	23.0	470	55
963	220				13.9	843	65-75						
1,658	44.8	5.1	279	75-80	7.4	258	70	9.7	322	60-65	12.2	320	55-60
1,683	44.8	4.9	302	75-80	7.3	310	65-70	9.5	364	60-65	11.7	358	55-60
3,226	100	2.11	436	90-100	3.13	875	75-80						
3,506	44.8	1.75	180	100	2.67	495	80-85	3.55	533	70-75	4.45	570	70
4,978	44.8	1.0	500	110	1.5	646	100	2.0	757	85-90	2.5	875	80
4,978	100				1.5	590-1400	105						
9,912	100				1.5	250-1110	220-250						

Table 7 - Coal dust explosibility tests (in % explosion*)
(Pittsburgh coal dust of -200 to +325 mesh size)

Nominal dust concentration g/m^3	Parameter	Unidirectional spark discharges with R = 5 k ohms				with R = 2 k ohms	Single pulse discharges R = 100 ohms	Oscillatory discharges R = 0
(wt of sample	W (mJ)	125	105	49	83	123	80-250	> 100
divided by vol	C (nF)	110	110	44.8	110	110	110	110
of Hartmann	V_o (kV)	30	25	30	15	15	15	12.5
chamber-1.23 L)	I_{o2} (A)	3.2	2.6	3	1.6	6.4	150	1100
	t (μs)	1550	1400	750	1250	750	50	12-36
	V_g (V)	75	80	75	105	90	50-150	varied
45				10				
66				30				
97				50				
142				60		30		
208				70		50		40
304		100	90	80	60	80		60
446				100		100	40	100
655							90	100

* % explosion represents an average of 10-20 tests.

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